THE EVALUATION OF SOIL EROSION OFF-SITES EFFECTS IN LARGE BASINS: THE STUDYCASE OF LERMA-CHAPALA WATERSHED, MEXICO

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INTRODUCTION

One of the primary global concerns during the new millennium is the assessment of the impact of accelerated soil erosion on the economy and the environment (Pimentel *et al.* 1995; Lal, 1995). Erosion damages the site on which it occurs and also has undesirable effects off-site in the larger environment. Erosion moves sediments and nutrients out of the land, creating the two most widespread water pollution problems in the rivers, lakes and dams. The nutrients impact water quality largely through the process of eutrophication caused by an excessive content of nitrogen and phosphorus. In addition to the nutrients presence, sediment and runoff may also carry toxic metals and organic compounds, such as pesticides (Brady and Weil, 1999; Lal, 1994; de Graaf, 2000; Renschler and Harbor, 2002). The sediment itself is a major pollutant causative agent, causing a wide range of environmental damages. The sedimentation of dams and canals, reduces their lifetime and efficiency, promoting a high restoration cost to the downstream users and affecting the national budget. In this sense, sedimentation knowledge is an important tool to guide spatial planning efficiently. Despite more than six decades of research, sedimentation is still probably the most serious technical problem faced by the dam industry (Mc Cully, 2001).

Many studies estimate present-day fluvial sediment and solute loads including both natural and accelerated soil erosion (Douglas, 1990). However, as Douglas mentioned (op.cit) many do not include all the erosion caused by human activity, because the eroded sediment is redeposited after a short movement downslope. Many soil particles are detached and carried downslope only to be held and trapped by a plant, tree or other obstacle a little further downslope. The sediment reaching the valley floor may not be completely removed by the river, but may be redistributed as alluvial floodplain deposits. The sediment transported downstream may be redeposited again on another part of the floodplain or in managed rivers in reservoirs.

In Mexico, recent studies applying the GLASOD method at 1:250,000 scale (SEMARNAT-Colegio de Posgraduados, 2002) indicate that 45% of the territory is being affected by man-induced soil degradation processes. According to the same study, soil water erosion affects 11 % of the territory, especially in areas of rain-fed agriculture (Bocco and Cotler, 2004). However, the actual impact and effect off-site is not completely known since parameters like for example, load carried by both overland flow and concentrated flow depends on the sediment size, shape and density being difficult to obtain and therefore very complex to estimate a real sediment production rate.

We are aware that quantifying transport processes at whole-catchment scale remains challenging, because of the complexity and variable nature of fluid flowpaths and chemical reaction mechanisms (Feng *et al*. 2004). Besides recent studies show that there is a paradox in catchment hydrology indicating that storm flow in some catchments is mostly “old” water (Kirchner, 2003).

Managing natural resources on watershed basis offer a geographic context within which the interactions of land, water and human activity can be understood, assessed, compared and monitored. In this context, there is a great need for assessing the consequences of land degradation in off-sites for achieving different options for restoration and protection of watersheds.

Most of the studies relating soil erosion and sedimentation are established in small watersheds that permit a detailed field calibration. However great part of the Mexican territory (43%) consists of large watersheds whose extension exceeds 20,000 km^2 consequently, the soil erosion and sedimentation research requires a different approach where the analysis of landscapes and sedimentation sampling at small scales (i.e. 1:250,000 scale) can be integrated in a GIS model.

Most of the sediment yield studies use long-term data with the purpose of applying different models of sediment transportation (Avendaño Salas *et al.* 1997; Poesen *et. al.* 2002; Jordan *et al*. 2005). However, as Bocco *et al*. (2005) states that in Mexico as in many Latin American countries there is lacking of relevant environmental data, gaps in the existent data sets or in many cases, this data has been incorrectly registered or is not updated.This situation affects also the hydrological investigation that is hindered by the scarcity of reliable long-term data, the exsisting networks are not very densely distributed or even nonexistent which hinders the application of hydrological models (Mendoza *et al.* 2002).

Under this context, , the development and application of alternative models for the estimation of sedimentation rates at medium regional scales are of vital significance, since the result derived from them allow to evaluate the different environmental situation of the watersheeds.

Working under a nonconventional perspective using an indirect approach requires the recognition and the spatial distribution of the biotic and abiotic components of the watersheds, as well as the spatial and temporal relationships between these factors under a geographical framework (Mendoza *et al*. 2002).

This paper presents the preliminary results of a sediment yield study in the Lerma-Chapala watershed related to the land use change and the water erosion in order to have a tool to guide properly the land use planning process under a a watershed management context.

Study Area and Methodology

The Lerma-Chapala watershed is located at the central part of Mexico (19°03'-21°34'N and 99°16'-103°31'W, Fig.1) covering an area of 53,591 km^2. The mean precipitation in the region is 735 mm, with a considerable variation from 1000 mm concentrates in the highlands areas in the south, while in the center and north part of the basin the precipitation is smaller (ca 300 mm). This precipitation rate along with the temperature, confer to the region a semi-arid climate with a rainy season in summer.

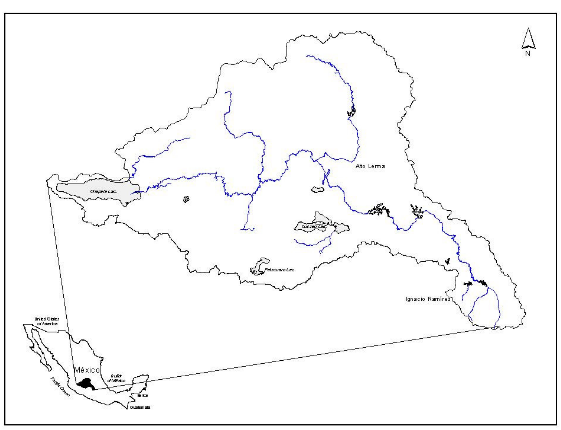

Figure 1. Location of Lerma-Chapala Basin in Mexico.

This watershed is located within Quaternary Volcanic Temperate Sierras therefore its main landforms are mountains and hills formed on volcanic extrusive and intrusive rocks as well as a lacustrian alluvial plain

Historically, the Lerma-Chapala basin has a long history of exploitation of its natural resources. Nevertheless, it was until the XX century and specifically after the 40's decade with the demographic growing, the industrialization process and the increase of irrigated agriculture took place. During the last 25 years (1976-2000) more than 1151 km^2 of temperate forest, 754 km^2 of tropical forest and 162 km^2 of scrubland were changed to cropland and pastures (Priego *et al*. 2004). The development of the agriculture and the industry was promoted by an intense hydraulic construction. Near of 555 dams, are distributed along the watershed, most of them constructed since 1950 (Cotler and Diaz, *in preparation*).

As a consequence 43% of the watershed presents different types of soil degradation. At the slopes of mountain and hills the water erosion dominates in form of rills and gullies (35% of the watershed). The presence of highly mechanized farming systems strongly influenced by the public policy, the markets and the agro-industries, cause the decline of the fertility (56%) and the salinization (2.7%) downslopes at the main valleys (Priego *et al*. 2004). Severe soil degradation has been not only reducing the sustainability and productivity of agricultural systems, but also causes sedimentation on rivers and dams.

Each altitude zone in a watershed has an overall hydrologic function to capture, store and safely release water. How well watershed is able to perform this overall function dependents upon how well each geomorphic component landform is functioning within the watershed. When one of this component becomes ecologically altered or degraded its ability to perform its natural hydrologic and geomorphic function becomes impaired and unable to perform properly (Petersen, 1999) causing the beginning of processes like soil erosion and sedimentation.

In a general way the altitude and stream order may be considered to make an spatial discrimination of the dominant processes in a watershed (table 1).

	High zone	**Medium zone**	**Low zone**
	Mountains and hills	Hills and valleys	Valleys and delta

Dominant ecological processes	Infiltration	Transport	Sedimentation

Table 1. Dominant processes in relation to altitudinal zone in a watershed

Our general framework takes into acount the spatial distribution of the current land use, the land use change and the soil erosion in form of gullies and rills mainly whitin a watershed context, as factors that promote the off-sites effects like sedimentation. In order to have a general idea about this situation we initiate our study making a sampling along the main rivers of 13 sub-watersheds of the Lerma-Chapala watershed (Figure 2).

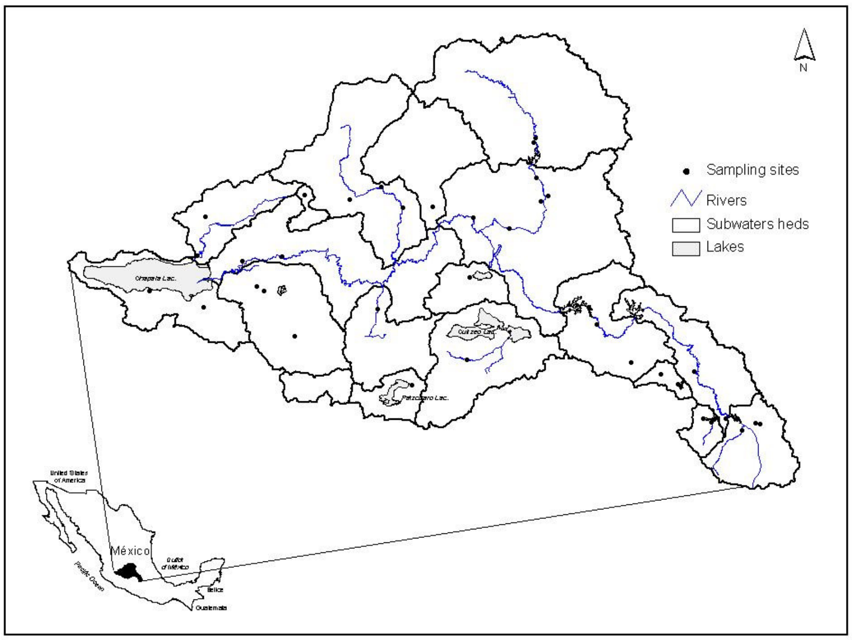

Figure 2. Sampling points at the Lerma-Chapala sub-watersheds

In each of these sub-watersheds we surveyed from 2 to 5 samples at the main perennial affluents to obtain the following data: (a) geometric properties of the stream channel as width, depth, stream type and (b) hydraulic properties of the channel as slope, hydraulic radio, streamflow discharge, velocity and the texture of the sediment. Each data was georreferenced and incorporated into a GIS.

The supply of material and streamflow depend upon the climate, topography, geology, soils, vegetation and land use practices on the watershed (Brooks *et al.* 1998). Therefore each mathematic model represents different conditions; there is not a universal equation applicable to all conditions. We choose the Meyer-Peter and Müller method (Simons and Sentürk, 1992) because its applicability to streamflow carries coarse and fine sediment.

This method is represented by the next formula:

$$q_{bw}^{2/3} = 39.25q^{2/3}S - 9.95D_s \text{,[Kg/m.s]}$$ [1]

RESULTS

At the Lerma-Chapala watershed, the areas of the sub-watersheds are very variable, from 307 to 7509 km^2 (Table 2). In there, the land use change, from primary and secondary vegetation to cultural uses in the 25 last years, vary from 9 to 41% of the area, being slightly higher at the highest zones. As a result, in the Lerma-Chapala watershed the distribution of water erosion in form of gullies and rills are concentrated at the high and medium zones of the watershed (Figure 3) causing the transport of sediment off-sites, especially at the medium and lower part of the watershed. However at this stage, the relationship between the land use change and the sediment yield is not clear yet.

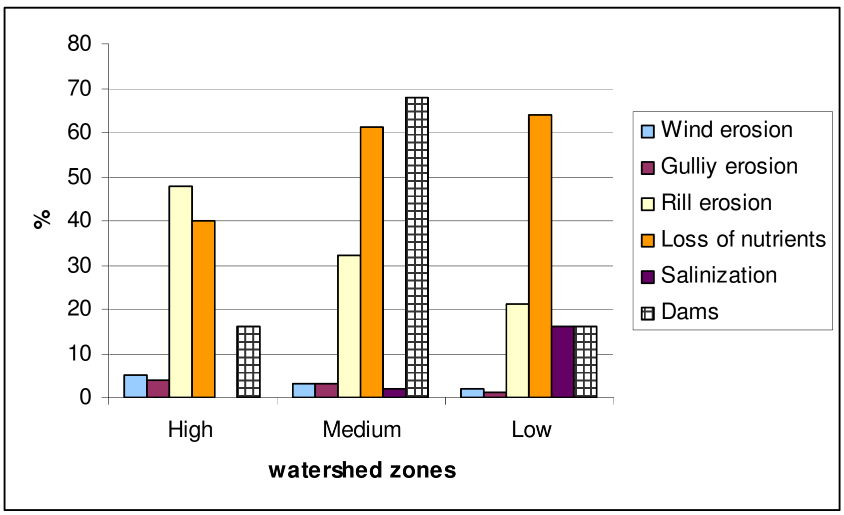

Figure 3. Soil erosion and dams (%) distribution at the Lerma-Chapala watershed

Generally, the gullies are formed at a piedmont with slopes of 1-5°, under rainfed agriculture (mainly oats, lucerne, beans and maize). The presence of the majority of the

[1] D_s sediment diameter (m)

q current stream discharge per unity of width

q_{bw} discharge in weight per unity of width and time

S slope

dams at the middle part of the watershed promotes the trapping of the sediment, especially the heavy gravels and cobbles that *starves* the river downstream of its normal sediment load.

Table 2. Soil erosion, land use change and sediment yield at the high and medium hydrological zones Lerma-Chapala sub-watersheds. The area (%) is related to each functional zone.

Sub-watersheds	**Area (km^2)**	**Hydrological functional zone**	**Erosion processes km^2 (%)**		**Primary and secondary vegetation change to cultural uses (1976-2000) (km^2 and %)**	**Current dominant land use**	**Estimated sediment yield (T $year^{-1}$)**
			Gullies	**Rills**			
Alto Lerma	7,509	High zone	28.98 (18.5%)	414.41 (26.2%)	185.2 (14.76%)	Temperate primary forest and secondary forest; Rainfed and irrigated agriculture	1740-4417
		Medium zone	127.41 (81.5%)	1166.12 (73.8%)	479.33 (7.66%)	Cropland, shrub, secondary temperate forest	
Chapala	3,312.7	High zone	13.6 (2.23%)	280.2 (46.3%)	63.8 (10.5%)	Pastures	2,672
		Medium zone	-	251.1 (35.5%)	32.8 (4.6%)	Rainfed and irrigated agriculture	
Cuitzeo	3,813.9	High zone	16.4 (1.8%)	138.2 (15.2%)	89.1 (9.8%)	Temperate primary forest and secondary	5,724
		Medium zone	36.9 (2.2%)	533 (31.1%)	238.2 (13.9%)	Pastures; rainfed and irrigated agriculture	
Duero	3,553.3	High zone	3.0 (0.29%)	353.7 (34.9%)	98.9 (9.8%)	Temperate primary forest and secondary; cultivated pastures	2208-4541
		Medium zone	61.0 (3.2%)	548.9 (29%)	111.83 (5.9%)	Pastures; rainfed and irrigated agriculture	
Ignacio Allende	6,914.2	High zone	5.5 (0.28%)	562.7 (28.7%)	105.3 (5.4%)	Temperate primary forest and secondary; natural pastures; shrubland.	1116-4012
		Medium zone	-	1846.9 (37.3%)	338.2 (6.8%)	Rainfed and irrigated agriculture	
La Pólvora	307.1	High zone	-	0.2 (0.24%)	13.13 (20.8%)	Cultivated pastures	14,928
		Medium zone	-	78.15 (32%)	52.16 (21.4%)	Rainfed and irrigated agriculture	

La Purísima	2,999.3	High zone	22.9 (4.06%)	149.9 (26.6%)	62.76 (11.2%)	Temperate primary forest and secondary; cultivated pastures	10,488
		Medium zone	79.7 (3.3%)	200.24 (8.2%)	91.6 (3.8%)	Rainfed and irrigated agriculture	
Lerma	5,058.5	High zone	8.0 (0.8%)	375.4 (37.8%)	123.2 (12.4%)	Secondary forest, cultivated pastures	9552-18,506
		Medium zone	-	0.07 (3.3%)	0.01 (0.5%)	Pastures; Rainfed and irrigated agriculture	
Pátzcuaro	935.7	High zone	2.9 (0.72%)	66.4 (16.4%)	41.8 (10.3%)	Temperate primary forest and secondary: cultivated pastures	36,792
		Medium zone	0.03 (7%)	-	0.1 (25%)	Rainfed and irrigated agriculture; pastures	
Turbio	4,802.9	High zone	0.1 (0.01%)	265.9 (28.3%)	97.8 (10.4%)	Natural pastures	684
		Medium zone	15.9 (0.4%)	766.5 (19.9%)	315.1 (8.2%)	Rainfed and irrigated agriculture	
Solis	3,002.8	High zone	10.8 (1.43 %)	138.9 (18.5%)	37.5 (5%)	Temperate primary forest and secondary; Rainfed agriculture	33,876
		Medium zone	-	416.7 (18.5%)	113.9 (5.1%)	Rainfed and irrigated agriculture; cultivated pastures	
Tepetitlán	369	High zone	1.5 (0.93%)	8.3 (5.14%)	13.02 (8.1%)	Rainfed agriculture and pastures	21,804
		Medium zone	-	128.4 (61.8%)	2.33 (1.1%)	Rainfed agriculture and pastures	
Zula	1,836.2	High zone	-	42.1 (9.8%)	91.8 (21.4%)	Cultivated pastures	52,068
		Medium zone	-	183.3 (13.1%)	109.3 (7.8%)	Rainfed and irrigated agriculture	

The sedimentation estimation was higher at the smaller sub-waterheds, until 3000 km^2 while at the greater ones the sedimentation yield is less important, the results were around the 10,000 ton year $^{-1}$ (Table 2 and Figure 4). This suggests a greater effect of dispersion and trapping of the soil particles along the slopes and the valley floodplains on bigger area.

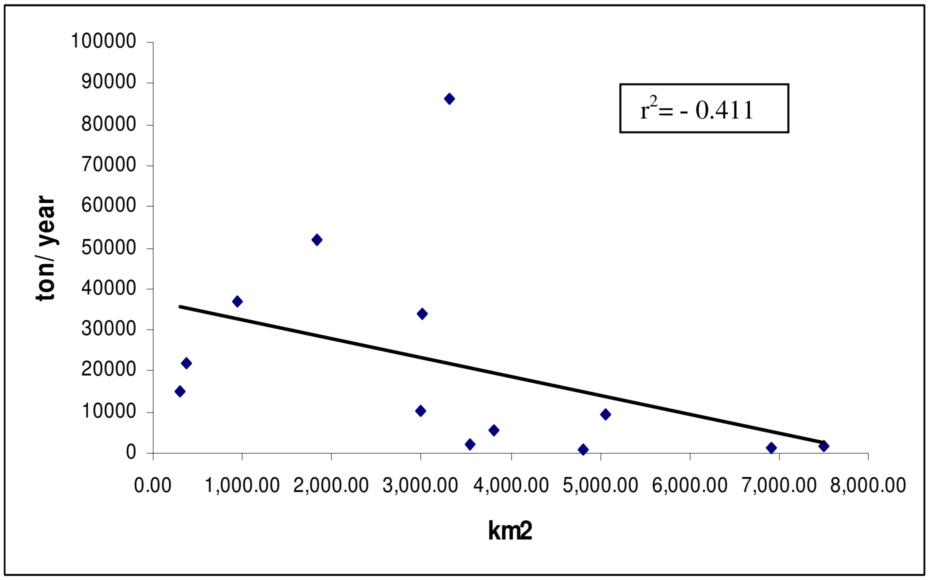

Figure 4. Relationship between annual sediment yield (ton year $^{-1}$) and sub-watershed area (km^2).

The preliminary obtained results show us an important sediment yield. Many factors could influence this process. For example, the presence of areas having rill erosion seems to be an indicator. There is a correlation between the rills-area less of 20% to sediment yield around 50,000-55,000 ton year^{-1}, when the rills are larger than 20% we have two panorama: the sediment yield is inferior to 20,000 ton year^{-1} or superior to 80,000 ton year^{-1}.

However at this stage of this study, these results were not able to provide stronger evidence of a significant association between land use change, soil erosion and sedimentation. It is necessary more detailed sampling and research in order to define a pattern that may explain better these relationships.

CONSLUSIONS

The environmental modification in Mexico resulted form the rapid process of land use change which causes at the same time serious land degradation. The main off-site consequence is the sedimentation of rivers and dams. This process causes changes in soil surface structure and nutrient budgets, carrying agricultural chemicals which pollutes streams and lakes; and at the surface water bodies leads eutrophication which affects aquatic life and water quality.

In this sense, sedimentation knowledge is an important tool to properly guide spatial planning.

One of the main restriction in developing countries is the lack of long-term hydrological data that difficult the application and accuracy of any model results. In face of the absence of long-term data, some mathematic models can sketch a scenario that allows to make a hierarchical zoning in function of environmental importance to guide some spatial use planning.

The preliminary results derived from the estimation applied in the Lerma-Chapala sub-waterheds show us an important sediment yield influence by tha area, the land use change and the soil erosion processes, among others factors. However at this stage, all the patterns are not clear yet.

We consider that the sediment yield could be a useful parameter at a national level being the base for making hierarchical zoning for prioritizing basins. But it is at regional and, even better, local levels where erosion studies should explain these processes so that policymakers can determine what kinds of institution (state or municipal) and public policy are needed (Cotler and Ortega, 2005).

REFERENCES

Avendaño Salas,C., E. Sanz Montero, R. Cobo Rayán, Gómez Montaña J.L. 1997. Sediment yield at spanish reservoirs and its relationship with the drainage basin area. Commission Internationale des Grands Barrages, XIX Congrès des Grands Barrages, Florence, Italy, 863-873pp.

Bocco G., A. Velázquez, Siebe C. 2005. Using geomorphologic mapping to strengthen natural resource management in developing countries. The case of rural indigenous communities in Michoacan, Mexico. Catena 60: 239-253.

Bocco G., Cotler H. 2004. Soil degradation and conservation in Mexico. Newsletter of the World Association of Soil & Water Conservation 20(3): 8-9pp, July-September. (http://www.swcc.cn/waswc/

Brady C.N., Weil R.R. 1999. The nature and properties of soils. Prentice-Hall 12th Edition, 881p.

Brooks N.K., P. Ffolliott, H. M. Gregersen, De Bano F.L. 1998. Hydrology and the management of watersheds. Panima Pu. Corp. Second Edition, 502p.

Cotler H. and S. Diaz (in preparation) Inventario y distribución de presas y bordos en la cuenca Lerma Chapala. Instituto Nacional de Ecología, México.

Cotler H., Ortega P. 2005. Effects of land use on soil erosion in a tropical dry forest ecosystem, Chamela watershed, Mexico. Catena (accepted).

De Graaf J. 2000. Downstream effects of land degradation and soil and water conservation. Land –water linkages in rural watersheds electronic workshop, 18 september-27 October, Background paper No. 5, Food and Agriculture Organization, 11p.

Kirchner J. 2003. A double paradox in catchment hydrology and geochemistry. Hydrological Processes 17:871-874.

Douglas I. 1990. Sediment transfer ans siltation. In. B.L. Turner, W.C. Clark, R.W. Kates, J.F. Richards, J.T. Matthews, W.B. Meyer (Eds.) The earth as transformed by human action. Cambridge Univ. Press, 215-234pp.

Feng X., J.W. Kirchner, Neal C. 2004. Measuring catchment-scale chemical retardation using spectral analysis and reactive and passive chemical tracers time series. Journal of Hydrology 292: 296-307.

Jordan G., A. van Rompaey, P. Szilassi, G. Csillag, C. Mannaerts, Woldai T. 2005. Historical land use changes and their impact on sediment fluxes in the Balaton basin (Hungary). Agriculture, Ecosystems &Environment (*article in press*).

Lal R. 1995. Global soil erosion by water and carbon dynamics. In: R.Lal, J. Kimble, E. Levine and B.A. Stewart (eds.) Soils and Global Change. Lewis Publishers, Boca Raton, Florida, pp. 131-140.

Mahmood K. 1987. Reservoir sedimentation, impact, extent and mitigation. World Bank Technical Paper n° 71, 134p.

Mas J.F., A. Velázquez, J. Reyes D., R. Mayorga-Saucedo, C. Alcántara, G. Bocco, R. Castro, T. Fernández, Pérez-Vega A. 2004. Assessing land use/cover changes: a nationwide multidate spatial database for Mexico. Int, J. of Applied Earth Observation and Geoinformation 5: 249-261.

Mc Cully P. 2001. Silenced rivers. The ecology and politics of large dams. Zed Books, 359p.

Mendoza M., G. Bocco, Bravo M. 2002. Spatial prediction in hydrology: status and implications in the estimation of hydrological processes for applied research. Progress in Physical Geography 26 (3): 319-338.

Nearing M.A., Lane L.J., Lopes V.L. 1994. Modeling soil erosion. In: Lal R. (Ed.) Soil erosion, reasearch &methods. Soil and water conservation Society, St. Lucie Press, 127-156 pp.

Petersen M. 1999. A natural approach to watershed planning, restoration and management. Wat. Sci. Tech. 39 (12): 347-352.

Pimentel D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri, Blair R. 1995. Environmental and economic cost of soil erosion and conservation benefits. Science 267:1117-1123.

Poesen J., Vandekerckhove, L. Nachtergaele J., Oostwoud W.D., Verstraeten G., van Wesemael B. 2002. Gully erosion in dryland environment. In: Bull, L.J., Kirby, M.J. (Eds.) Dryland Rivers: Hydrology and Geomorphology of Semi-Arid Channles. Wiley, Chichester, UK,pp. 229-262.

Poesen J., J. Nachtergaele, G. Verstraeten, Valentin C. 2003. Gully erosion and environmental change: importance and research needs. Catena 50:91-133.

Priego A., Cotler H., Fregoso A., Luna N., Enriquez G.C. 2004. La dinámica ambiental de la cuenca Lerma-Chapala. Gaceta Ecológica 71: 23-38pp, Instituto Nacional de Ecología (www.ine.gob.mx), México..

Renschler C., Harbor J. 2002. Soil erosion assessment tools from point to regional scales-the role of geomorphologists in land management research and implementation. Geomorphology 47(2-4):189-209.

Simons D.B., Sentürk F. 1992. Sediment Transport Technology. Water and Sediment Dynamics. Water Resources Publications, Littleton, Colorado.